Generation of high-quality signals for optical sensing using DFB lasers injection locking

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ABSTRACT

Injection locking of two DFB semiconductors opens new possibilities to generate effective signals for optical sensing, in order to reach better performances. Pure waveforms can be generated with qualities exceeding those obtained using external modulators.

Keywords: Injection locking, DFB laser, optical sensor.

1 INTRODUCTION

The injection of a weak periodic signal into a more powerful free-running oscillator may give rise to a variety of injection locking phenomena. Typically the initially free-running oscillator (named the *slave* oscillator) leaves its own resonant frequency to synchronize itself with the external signal; it then gets phase locked to the injected signal from the so-called *master* oscillator, which thus controls the slave oscillator without being influenced by this latter. Injection locking effects may occur in virtually any kind of self-sustained oscillators, such as mechanical, electrical and laser oscillators.

In this paper we shall address the important case for applications in which two DFB semiconductor lasers are in a master-slave configuration. We first present the advantages of injection-locking for optical signal processing and then show that the benefits of injection locking go beyond the simple case of a faithful replication of the master spectrum by the slave. A great variety of imaginative configurations may be defined, combining injection-locked modulated lasers, which results in the effective generation of various signals, such as pure AM, pure FM, frequency-shifted or frequency sweeping optical waveforms.

2 PRINCIPLE

The experimental realization of an injection-locking using pigtailed DFB lasers is in essence extremely simple, as shown in Fig. 1. Care must be only taken to properly isolate the master laser from any light injection from the slave and to make the polarisation states of the 2 lasers matched within the slave cavity.

An important parameter is the so-called *static locking range* $\Delta\nu_{max}$, that corresponds to the maximum difference between the free-running frequencies of the master and the slave making the frequency locking possible. In other words the frequencies of the 2 lasers must be tuned to lie within an interval $\Delta\nu_{max}$ to enable the stable locking of the slave onto the master frequency.

According to standard models the static locking range is closely related to the ratio ρ between the injected master and the slave emission powers within the slave cavity [1,2]. It follows a square root relationship:

$$\Delta\nu_{\max} = \frac{V_g}{2L}\sqrt{(1+\beta_c^2)\rho}$$

where V_g is the group velocity, L the laser cavity length, and β_c is the linewidth enhancement factor.

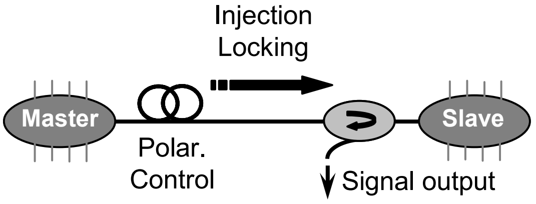

Fig 1 Basic injection-locking configuration of 2 DFB semiconductor lasers. The circulator isolates the master from any light of the slave and provides a lossless output.

This equation shows that the higher the power injection ratio ρ, the broader the frequency locking range $\Delta\nu_{max}$. It turns out actually in standard DFBs that for values of ρ above $2\cdot10^{-5}$ unwanted relaxation oscillations are observed in the slave spectrum. And for $\rho > 2\cdot10^{-4}$ the spectrum turns fully chaotic [1]. For ρ=$2\cdot10^{-5}$ the static locking range $\Delta\nu_{max}$ is typically between 500 MHz and 1 GHz. It means that the free-running frequencies of the 2 lasers must be initially very close to observe injection locking.

Inversely a power injection ratio below 10^{-6} results in an injected power so low that it is dominated by the Rayleigh scattered slave light from the pigtail and to a static locking range comparable to the laser linewidth.

In summary a power injection ratio in the range of 10^{-5} is ideal to properly achieve injection-locking. This corresponds approximately to the amount of power that leaks through a standard isolator in the isolating direction, so that a standard DFB isolated pigtailed module can often be used unmodified for injection locking by simply feeding the master light into the slave pigtail and then through the built-in isolator. This injection ratio condition is valid for static emission. When the lasers are modulated and the emission frequency is swept, a higher ratio is usually required for a proper locking.

3 CONFIGURATIONS FOR THE GENERATION OF ADVANCED SIGNALS

Beyond the trivial case of injection locking when the slave laser simply perfectly replicates the master CW emission, it is less known that more interesting configurations can be set up to achieve more sophisticated signals. In particular the traditional drawback of mixed FM-AM modulation resulting from the direct modulation of a laser diode can be overcome to a wide extent using injection locking. Traditionally pure AM, FM and SSB modulation spectra are obtained using a single or a combination of expensive external modulators. It will be demonstrated here that the same result can be achieved with excellent performances using an injection-locking scheme with 2 DFB lasers. This solution turns out to be frequently very cost-effective with signals of quality outperforming those generated by external modulators.

3.1 Pure AM modulation

This is achieved by operating the master laser in CW mode and modulating the current of the slave at the modulation frequency. The carrier of the slave locks on the master emission line, resulting in no frequency dithering and therefore no unwanted FM modulation, as shown in Fig. 2. It can be observed that the spectrum is substantially narrowed and becomes symmetrical as expected for pure AM, while the time response is unchanged with or without locking. The amount of injected power into the slave must be carefully adjusted to obtain the proper emission characteristics.

3.2 Pure FM modulation

In this case the current of the master laser is modulated at the modulation frequency while the slave is operated in CW mode. The instantaneous frequency of the slave laser locks onto the instantaneous emission line of the master. The slave shows no significant change of its emission power, resulting in a pure frequency dithering, as shown in Fig 3 where the slave spectrum is broad and symmetrical. While the master shows in the time domain an important AM modulation as expected from direct modulation, no AM modulation is observed in the slave emission demonstrating the pure FM modulation. Here the operating condition requires that the instantaneous frequency range lies within the locking range.

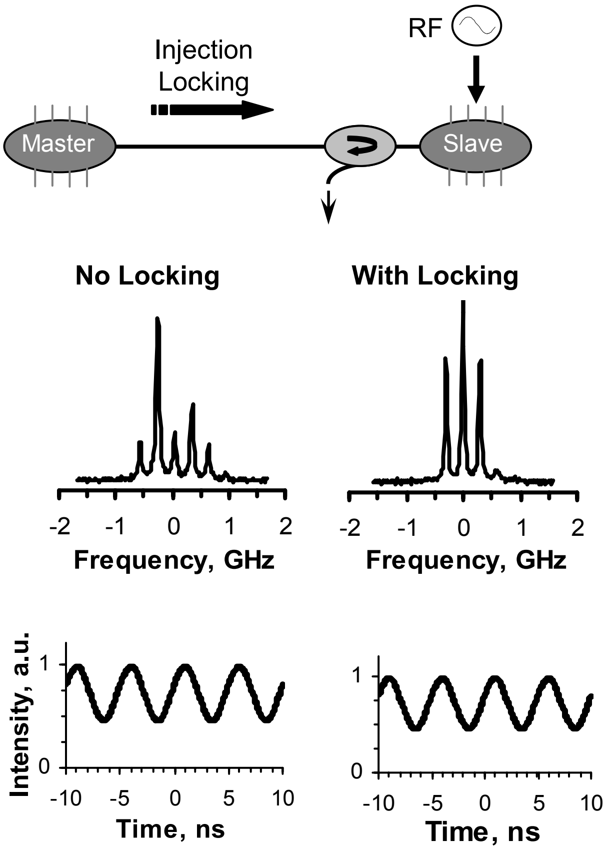

Fig 2 Injection-locking configuration for pure AM modulation. Spectrum and time-domain waveform of the slave laser is shown before and after locking to the master laser

3.3 SSB modulation (optical frequency shifting)

This is simply achieved by modulating the current of the master laser and by locking the slave on one of the modulation sidebands. The frequency difference of the 2 lasers is thus perfectly stable [2,3,4]. The experimental configuration is identical to that shown in Fig. 1, the only difference being that the modulation frequency exceeds the locking range, so that only one frequency component of the modulation spectrum matters for injection locking. It must be pointed out that the slave laser may be locked as well on a higher-order sideband, resulting in an optical frequency difference that is a multiple of the applied modulation frequency. This is particularly convenient in the microwave domain and locking up to the fifth harmonic was successfully achieved in our team [2].

It is also possible to apply the current modulation to the slave and to obtain the same result. In this case the experimental configuration is identical to Fig. 2 and one of the modulation sideband of the slave laser locks onto the master CW emission. This is formally equivalent when one considers the modulation process in the laser as a coherent coupling between two waves separated by a frequency given by the modulation. Of course an external modulator of any type can be used as well. Such a scheme may be more convenient in some experimental configurations, such as for Brillouin fibre sensing for which this technique was successfully demonstrated [5].

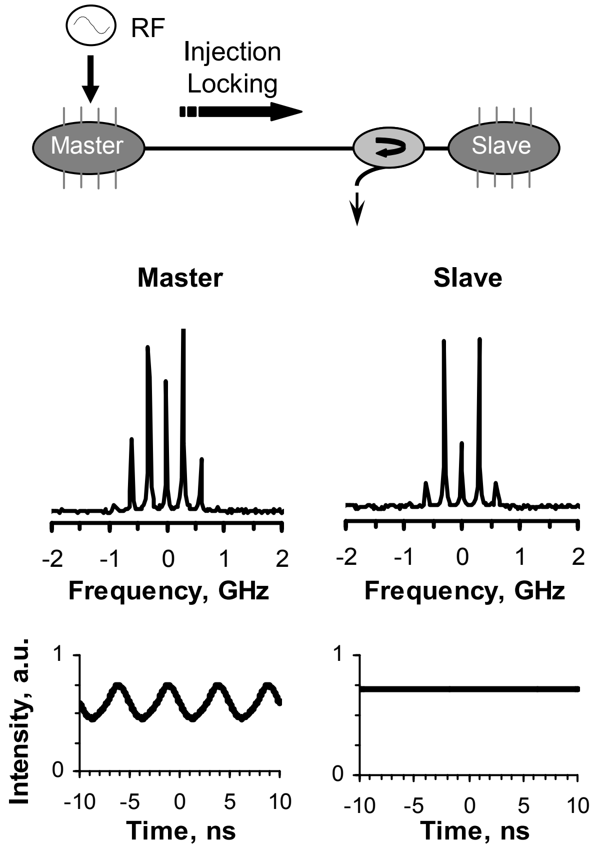

Fig 3 Injection-locking configuration for pure FM modulation. Spectra and time-domain waveforms of the master and of the slave laser are shown.

3.4 Frequency sweeping (broadband FM)

It is possible to generate a broadband frequency dithering with no amplitude modulation using a special scheme based on a delay line and the self-injection locking of a single laser [6]. As shown in Fig. 4 the laser light is first phase modulated using an external modulator that may be simply a segment of optical fibre wrapped around a piezoelectric trans-ducer (PZT). This modulator makes the instantaneous frequency of the laser light to be sinusoidally modulated, at a rate given by the frequency of the electric signal applied to the PZT and an amplitude related to the phase modulation index.

This signal propagates through the fibre delay line and is then fed back into the laser cavity. The laser frequency locks on the feedback signal, showing a sinusoidal modulation of the instantaneous frequency, accordingly.

If the PZT modulation period is equal to the round trip time of the delay line, the signal is then modulated again synchronously and the instantaneous frequency shows double sweep amplitude. This process works as well if the PZT frequency is an integer multiple of the round-trip frequency. This signal is then fed back into the laser that locks on to this doubled sweep amplitude signal. The frequency variations then add up constructively at each round trip, as shown in Fig. 5, until the sweep amplitude corresponds to the locking range.

When the edges of the locking range are reached the laser can no longer lock on frequencies out of the locking range and the sweeping amplitude stops to grow, reaching a steady state. The obtained spectrum of the laser, shown in Fig. 6, is typical of a broadband FM

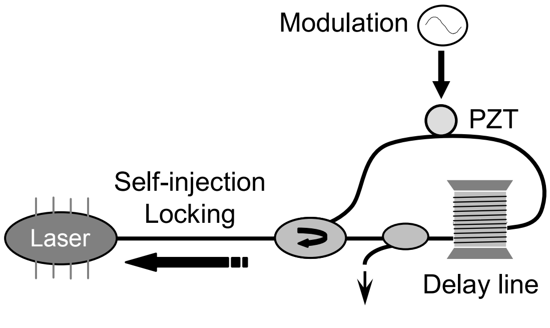

Fig. 4 Injection-locking configuration for frequency sweeping generation. The slave laser is locked on its own emission, after phase modulation and a time delay resonant with the modulation.

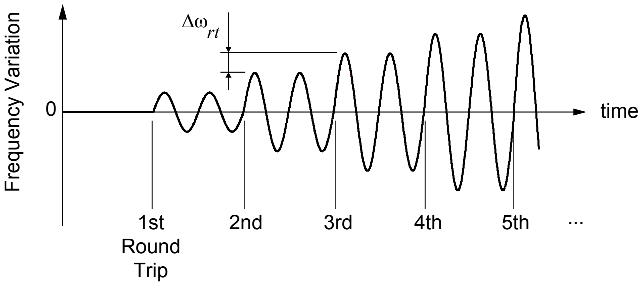

Fig. 5 Instantaneous frequency variation of the fed back light at the laser input after 1,2,3,… round trips in the fibre loop. Owing to resonant phase modulation, the frequency variations add up constructively at each round trip, $f_m = 2f_o$ in the illustrated case. 0 indicates the emission frequency of the free-running laser.

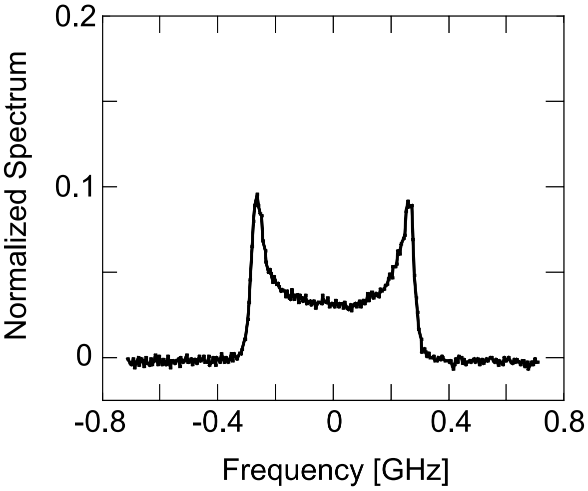

Fig. 6 Power spectrum of the self-injection locked slave laser with resonant phase modulation ($V_m/V_\pi \cong 0.27$, f_m = 1.15 MHz). The feedback level is 9×10^{-5}.

modulation. By properly adjusting the fed-back power the frequency sweeping amplitude can be tuned, accordingly. Amplitudes up to 10 GHz are theoretically possible with a high fed-back power. This is impossible to obtain without a severe amplitude modulation using a direct current modulation. This opens a wide field of possible applications in gas traces spectroscopy using laser diodes and in correlation-based distributed Brillouin sensing.

3.5 Conclusion

In this paper we present the high potentialities of injection locking applied to 2 DFB lasers for the generation of high quality signals for sensing applications. The obtained signals outperforms in most cases those generated using external modulators at a reduced cost. The generation of pure AM, FM, frequency-shifted and frequency-swept signals are experimentally demonstrated.

Other smart configurations are certainly possible using the large potentialities of injection-locking and this opens a wide area for the creativity in this research field.

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